# A weak parton shower

## Implementation and phenomological studies at 100 TeV

based on JRC and T. Sjöstrand, JHEP 04 (2014) 115 (arXiv:1401.5238 [hep-ph])

Jesper Roy Christiansen

Department of Astronomy and Theoretical Physics
Lund University
MCnet short-term student at CERN until June 1.

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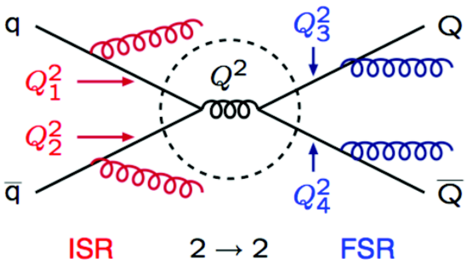
# Motivation

- Huge focus on QCD corrections at LHC
  - Automatized NLO calculation tools
  - Understanding of subjet structure
- Weak correction scales with energy $\alpha_{\mathrm{W}} \ln^2(E^2/M^2_{\mathrm{W/Z}})$
- Emissions of W/Z changes the event structure
  - Possible to have additional hard leptons

# The parton shower approach

$2 \to n \quad = \quad (2 \to 2) \oplus \text{ISR} \oplus \text{FSR}$




Iterative structure of emissions, with simple DGLAP splitting kernels

FSR = Final-State Radiation = timelike shower
$Q_i^2 \sim m^2 > 0$ decreasing

ISR = Initial-State Radiation = spacelike showers
$Q_i^2 \sim -m^2 > 0$ increasing

Showers are unitary: do not (explicitly) change cross sections; emission probabilities do not exceed unity — Sudakov factor.

# Parton shower vs fixed ME calculations

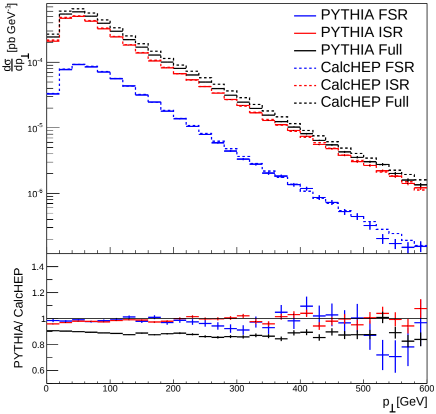
- Advantages
  - The PS is fast
  - It is (almost) process independent
  - Can handle any number of emissions
  - Includes Sudakov form factors (resummation)
- Disadvantages
  - Approximative to (improved) LL
  - Not possible to choose specific phase-space areas
  - No uncertainty estimate

# What is different for a weak PS

- The W/Z bosons are massive
- The couplings are spin-dependent
  - Keep track of spin throughout the shower
  - Assume spin averaged fermions from hard process
- Flavour change for W emissions
  - Full CKM (except top) is included
  - PDF change for initial state radiation
  - Possible Bloch-Nordsieck violation not accounted for in the shower

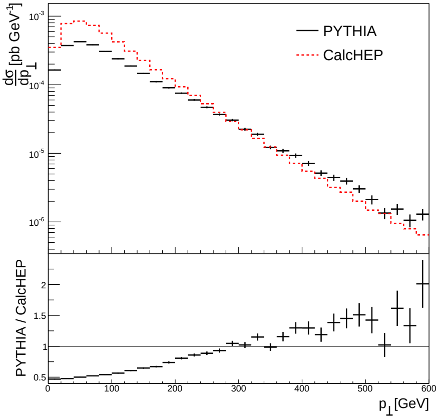
# What is different for a weak PS (II)

- The DGLAP splitting kernel ($\frac{1+z^2}{1-z}$) is no longer a good approximation
- But it can still be used as an upper estimate, and later be corrected by the $2 \to 3$ ME



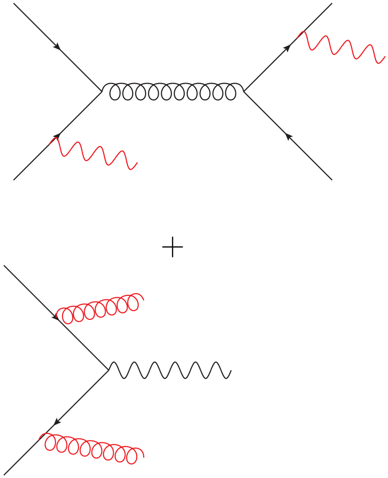
# Some caveats

- Works best if hard process is a QCD process
  - The right figure shows $u\bar{u} \to u\bar{d}W^-$ with only EW diagrams, thus worst case scenario
- Radiation only implemented off quarks and leptons (no $Z \to W^+W^-$, ..., no BSM)



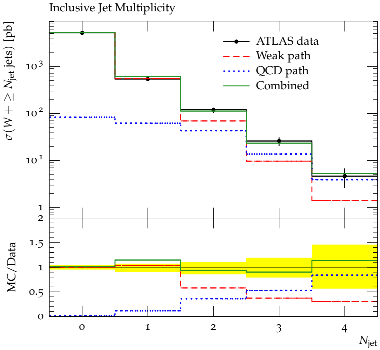
# W + jets - The PS way

- Combine Drell-Yan W production with QCD radiation and $2 \to 2$ hard QCD processes with weak shower
- Black part is calculated with ME and red part comes from the PS
- Double counting avoided by applying cuts in the spirit of the $k_\perp$ jet algorithm



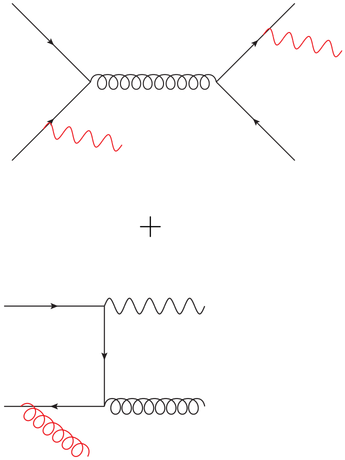
# W + jets at 8 TeV

- The PS prediction for W + jets is known to not describe data well
- k-factor applied (normalized to fit first bin)

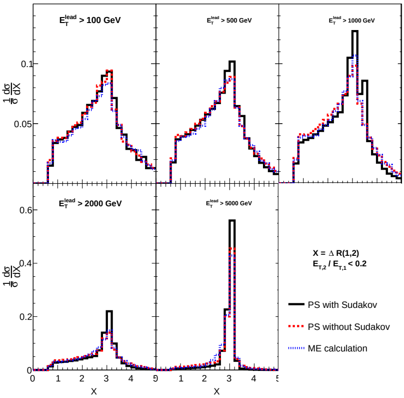


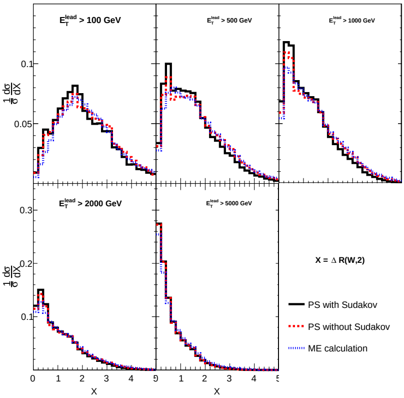
# W + jets at 14 TeV

- Only two QCD partons are allowed (to be similar to ME)
- $\Delta R(\text{jet }1, \text{jet }2) > 0.7$ and $p_{\perp}^{\text{jet}} > 30$ GeV
- Instead of normal Drell-Yan use $\text{pp} \to \text{W}^{\pm}\text{j}$ to gain better statitics for high $E_{\perp}$
- Allow PS to go to kinematical limit (power shower)
- Contains both weak and QCD Sudakov form factors from the shower
- Thanks to M. Mangano for providing the ME calculations

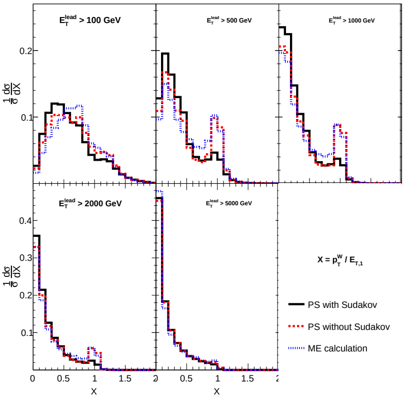


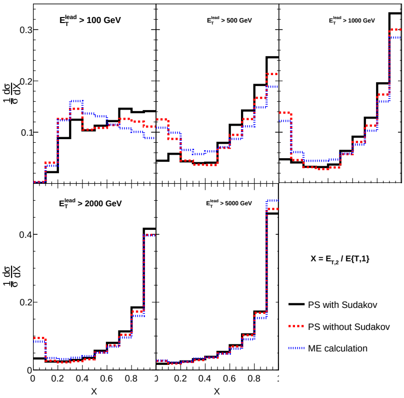
# W + jets at 14 TeV (angular distributions)



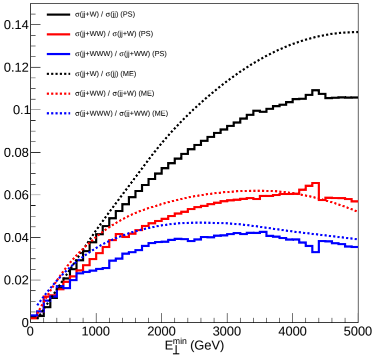



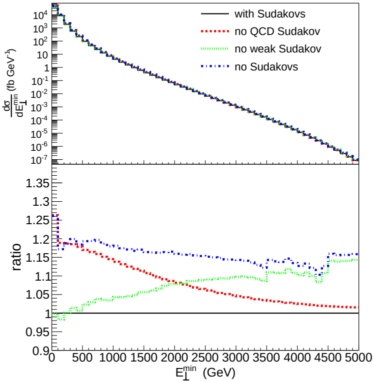
# W + jets at 14 TeV (energy distributions)



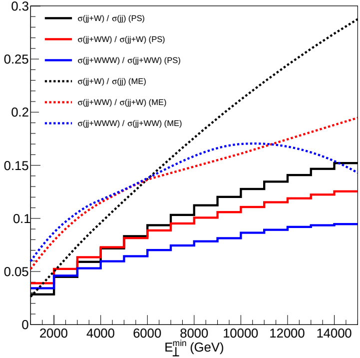
# W + jets at 14 TeV

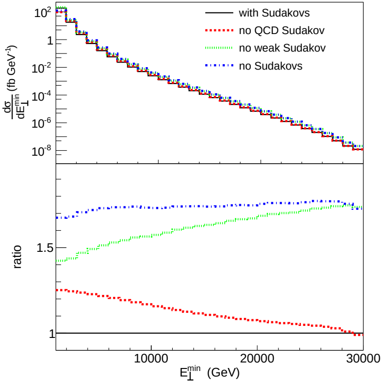



- Needs to be inclusive in weak emissions
- Resummation effects of the order of 20 %

# W + jets at 100 TeV

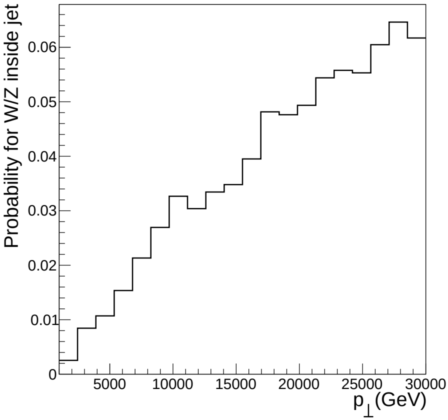



- Needs to be inclusive in weak emissions
- Resummation effects of the order of 70 %

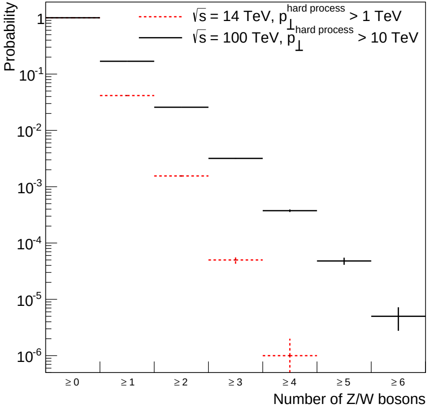
# Weak bosons inside jets

- Look for W/Z inside high $p_\perp$ jets:
  - $k_\perp$-jet algorithm with $R = 0.4$
  - W and Z participating in jet clustering
  - Remove isolated W and Z jets
- How problematic is this background for top identification? - See talk by M. Selvaggi



# Multiple weak emissions

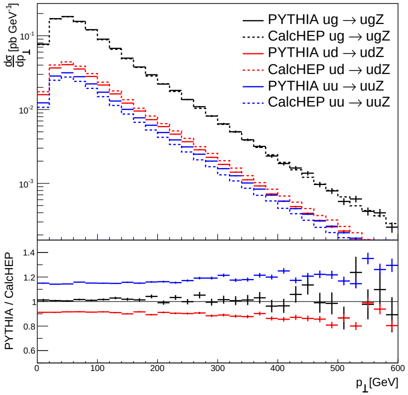
- Simple to extend to multiple emissions
- Includes both W/Z emissions
- (Remember radiation from gauge bosons not included)



# Conclusion

- Explained the implementation of a weak shower within PYTHIA (fully implemented since public version 8.183, with some small bug fixes in 8.185) - off by default to avoid unintended double counting
- Weak corrections need to be included in events with high $E_\perp$
- Also need to include weak Sudakov factors at high $E_\perp$
- Future studies
  - Comparison with both EW and QCD NLO caluclation
  - Comparison to merging techniques

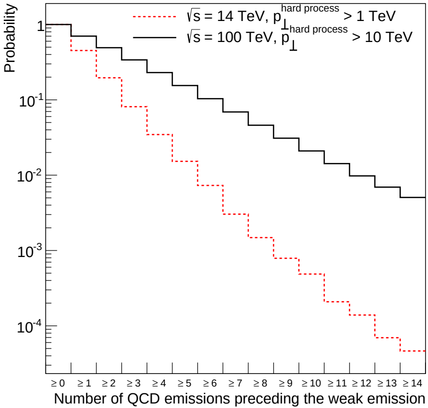
# t-channel validation




- Comparison of t-channel processes between PYTHIA and CalcHEP
- $p_\perp(u) > 100$ GeV, $M(u,u) > 150$ GeV and fixed scales at $m_Z$
- PS is not always an overestimate of the ME.

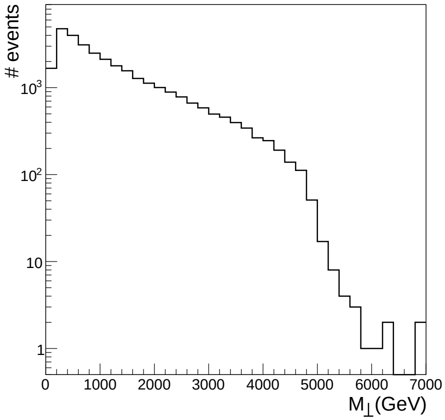
# Competition between QCD and weak emissions

- Need to include up to 11 emissions, to only miss 1 %
  $\Rightarrow$ Does this become problematic for merging techniques?



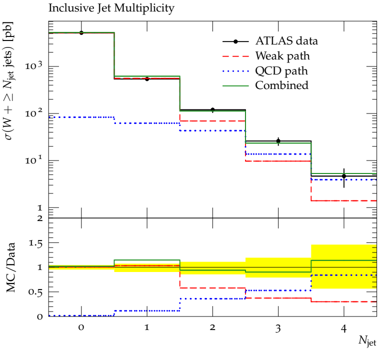
# Mono Z

- Similar to mono jet searches, just searching for Z bosons instead
- Also possibility for WIMPs to radiate Z in FSR - any use?
    - Simple study of $Z' \to \nu\bar{\nu} \to \nu\bar{\nu}Z$, with $M(Z') = 5$ TeV
- (Weak radiation for BSM particles not yet implemented)

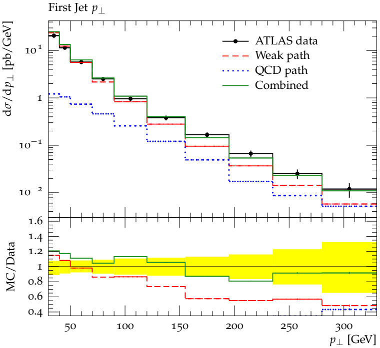


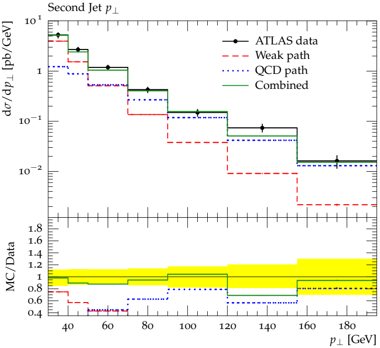
# W + jets

- W + jets is notoriously known for being difficult to describe data for pure PS approaches
- Combine Drell-yan W production with QCD radiation and $2 \to 2$ hard QCD processes with weak shower
- Double counting avoided by applying cuts in the spirit of the $k_\perp$ jet algorithm



# W + jets


First Jet $p_\perp$
dσ/d$p_\perp$ [pb/GeV]
ATLAS data
Weak path
QCD path
Combined
MC/Data
$p_\perp$ [GeV]


Second Jet $p_\perp$
dσ/d$p_\perp$ [pb/GeV]
ATLAS data
Weak path
QCD path
Combined
MC/Data
$p_\perp$ [GeV]

# W + jets

- The $\varphi$-angle between the two jets is not that well described by PYTHIA.
- It shows the limitation of the PS approach.